Construction and Building Materials 149 (2017) 395–405

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Shear and flexural strength prediction of corroded R.C. beams

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HIGHLIGHTS

- Experimental versus analytical prediction of effects of general and pitting corrosion on steel bars.
- Experimental versus analytical prediction of effects of general and pitting corrosion on R.C. cross-section if flexure.
- Experimental versus analytical prediction of effects of general and pitting corrosion on R.C. beams in shear.
- Case of study for strength and ductility degradation in flexure and shear of R.C. beams under natural corrosion scenarios.

ARTICLE INFO

Article history:
Received 16 January 2016
Received in revised form 21 April 2017
Accepted 12 May 2017

Keywords:
Shear-moment interaction
Corrosion
Bond
Pitting
Flexural response

ABSTRACT

The purpose of the work was the study of the structural safety of R.C. beams subjected to corrosion processes though the derivation of moment-curvature diagrams and moment-to-shear interaction diagrams. Normal-strength reinforced concrete beams with longitudinal bars in the presence of transverse stirrups and subjected to corrosion processed are considered.

Experimental results available in the literature related to corrosion processes, for steel bars, crack openings and bond degradation due to rust formation are reviewed. Then analytical laws relating to crack opening, bond degradation with attack penetration depth, through a rearranged form of Faraday's law, are presented. An analytical model for cross-section analysis and shear strength prediction including the main effect due to rust formation is developed and verified against experimental data. Finally, a case study is added giving moment-curvature diagrams and moment-to-shear interaction diagrams to show the effects of different scenarios of natural corrosion increasing with time on beam elements.

1. Introduction

Corrosion of reinforcing steel is one of the main causes of deterioration of reinforced concrete structures and affects both ultimate and serviceability conditions [1,2]. Its effects include cracking and spalling of the concrete cover, reduction and loss of bond between concrete and corroding reinforcement, and reduction of the cross-sectional area of the reinforcing steel (longitudinal bars and stirrups).

Reinforcing steel is normally passive in concrete due to high alkalinity of the concrete pore solution. However, penetration into the concrete of chlorides or carbonation destroys this inhibitive property of the concrete and leads to corrosion. Two types of corrosion of reinforcement can affect an R.C. structure: general and pitting. General corrosion affects a substantial area of longitudinal and transverse reinforcements with more or less uniform metal loss over the perimeter of the reinforcing bars. It also causes cracking and possibly spalling and delamination of the concrete cover and produces rust staining on the concrete surface. Pitting is a localized corrosion type, which concentrates on small areas of reinforcement, causing spalling of the concrete cover.

Nondestructive tests allows one to establish the presence of carbonation in concrete (carbonation test) and/or the presence of chlorides (chloride content) and to know whether the corrosion processes are ongoing. Also, nnondestructive testing allows one to estimate for general corrosion the reduction of the area of steel reinforcements through the gravimetric method and allows one to estimate the pit in the bar for chloride attack.

Numerous experimental studies have investigated the effects of corrosion of materials such as on steel bars [3–4], steel-concrete bond [5–8], etc. There have also been studies at a structural level, relative for example to the flexural behavior of beams [9–13] and columns [10].

To reproduce the corrosion process in a laboratory, high intensities of current are used (ranging between 100 $\mu A/cm^2$, used by [11] and 3000 $\mu A/cm^2$, used by [5]); the duration of the tests is reduced to a few months or even a few days. In in situ structures,

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http://dx.doi.org/10.1016/j.conbuildmat.2017.05.125
0950-0618/

Nomenclature

A_s	cross-sectional area of longitudinal bars
A_p	area of pit
$A_{s,pit}$	reduced area of steel bars due to pitting
$A_{s,red}$	reduced area of steel bars due to general and pitting corrosion
$A_{st,red}$	reduced area of stirrups
A_{st}	section of tie transverse steel
a	shear span
b	beam section width in the virgin state
b_f	beam width increased by corrosion cracking
d	distance from the extreme compressive fiber to the centroid of the tension reinforcement
D	bar diameter
D_{eq}	equivalent diameter of longitudinal bars
D_{st}	diameter of stirrups
E_c	modulus of elasticity of concrete
E_s	modulus of elasticity of steel
f_c	mean value of concrete compressive strength
f_c^*	reduced concrete strength
f_y	yield stress of longitudinal bar (or tie)
f_{ys}	yield stress of stirrups
H	height of beam
i_{corr}	current intensity
j	coefficient related to internal arm
jo	coefficient related to internal arm in the loaded section
k	coefficient related to bar roughness and diameter
K	coefficient related to concrete
L	length of beam
l_{anc}	anchorage length
M_{uc}	ultimate moment due to compression failure
M_{uy}	ultimate moment due to yielding of reinforcement
M_{us}	ultimate moment associated with shear failure
N_c	ultimate axial force
n_{bars}	number of bars in one layer
$p(t)$	depth of pit
q_{res}	post-peak bond strength
R	pitting coefficient
S	depth of carbonation
s	tie spacing
$u_{i,corr}$	opening of corrosion crack
V	shear force
V_a	contribution of shear force due to loss of bond in anchorage zone
V_b	contribution of shear force due to the beam effect
V_c	contribution of shear force due to crushing of the concrete
v_a	dimensionless contribution of shear force due to loss of bond in anchorage zone
v_b	dimensionless contribution of shear force due to beam effect
v_c	dimensionless contribution of shear force due to crushing of concrete
v_{st}	dimensionless contribution of shear force due to stirrups
v_u	dimensionless shear stress
X	corrosion attack depth
X_p	loss of mass of steel bar
x_c	position of neutral axis
w_{cr}	total crack width for one corrosion level
α	stress block coefficient
α_{pit}	percent reduction of bar cross-section due to pitting
α_{pit}^{max}	value of percent reduction of bar cross section causing complete loss of ductility for pitted bars
β	stress block coefficient
γ	dimensionless post-peak bond strength
δ	concrete cover thickness
ΔA_{pit}	bar cross-section area reduction due to pitting
ε_0	strain at peak compressive stress for concrete
ε_1	transversal strain of corroded beam
ε_{cu}	ultimate strain of concrete
ε_{su}	ultimate strain for steel
ε_{su}'	ultimate strain for steel of pitted bars
ε_{sy}	yield strain for steel
θ	angle related to limit state governed by crushing of concrete
μ	ductility of member
μ_{corr}	ductility of corroded members
ν	softening coefficient
ν_{rs}	volume expansion ratio between rust and steel
ρ	geometrical ratio of steel bars
ρ_s	geometrical ratio of stirrups
ψ	ratio between mean value of concrete compressive strength and reduced concrete compressive strength
ϕ_s	curvature at yielding
ϕ_{su}	curvature at failure of steel bars
ϕ_{cu}	curvature at compression failure
ω	mechanical ratio of steel bars

natural processes are characterized by lower current intensity and longer process times.

Natural processes are characterized by an intensity i of about 1 μA/cm^2 and duration of the phenomenon comparable with the useful service life of the construction. For natural corrosion conditions, Table 1 gives the qualitative correlation between corrosion current (μA/cm^2) and corrosion of the rebar obtained with the linear polarization method (LPR), as suggested in [14].

To describe the structural behavior of corroded beams, most studies are based on numerical analyses carried out with the finite element method [3,12]. These are complex and require detailed information on the constitutive laws of the damaged materials. Numerical analyses to calculate the effects of corrosion on mechanical parameters are carried out in [13]. In this paper, a simple approach based on sectional analysis in flexure and on a truss model in shear is utilized. Since it allows manual calculation, it can be considered a useful instrument for preliminary verification of the safety state in a deteriorated structure or prevision of its residual life [15]. It has to be stressed that the aim of this paper was also to show through moment-curvature diagrams and moment-to-shear interaction diagrams the effects of different corrosion scenarios increasing with time on beam elements.

Table 1
Corrosion current vs. condition of the rebar.

Corrosion current (μA/cm^2)	Condition of rebar
$\leqslant 0.1$	Passive
$0.1 \div 0.5$	Low to moderate
$0.5 \div 1.0$	Moderate to high
$\geqslant 1.0$	High corrosion rate

2. Effect of corrosion on concrete and steel reinforcements

The main effects due to corrosion of longitudinal and transverse steel in R.C. beams, widely observed experimentally [11], are the following: – reduction of the steel area in the longitudinal bars